Session 11, S12

Highlights from a Recent BEUV Source Workshop & Activities

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2012 International Workshop on EUV and Soft X-Ray Sources
October 11th, 2012, UCD, Dublin, Ireland

JSAP, JPS, LSJ Ad-hoc workshop

Sep. 11th: JSAP @ Matsuyama

Sep. 18th: JPS@Yokohama

Sep. 26th: LSJ@Ashikaga

Academic Activities in Japan

Ad-hoc EUV & BEUV workshop
On Sep. 26, half-day

Since 839 or 842???

Workshop’s participants: 32 members

Kumamoto University

UCD
DUBLIN

Speclab

ILT
Institute for Laser Technology

JAEA

NIFS

Nikon

Canon

NTT AT

SAMSUNG

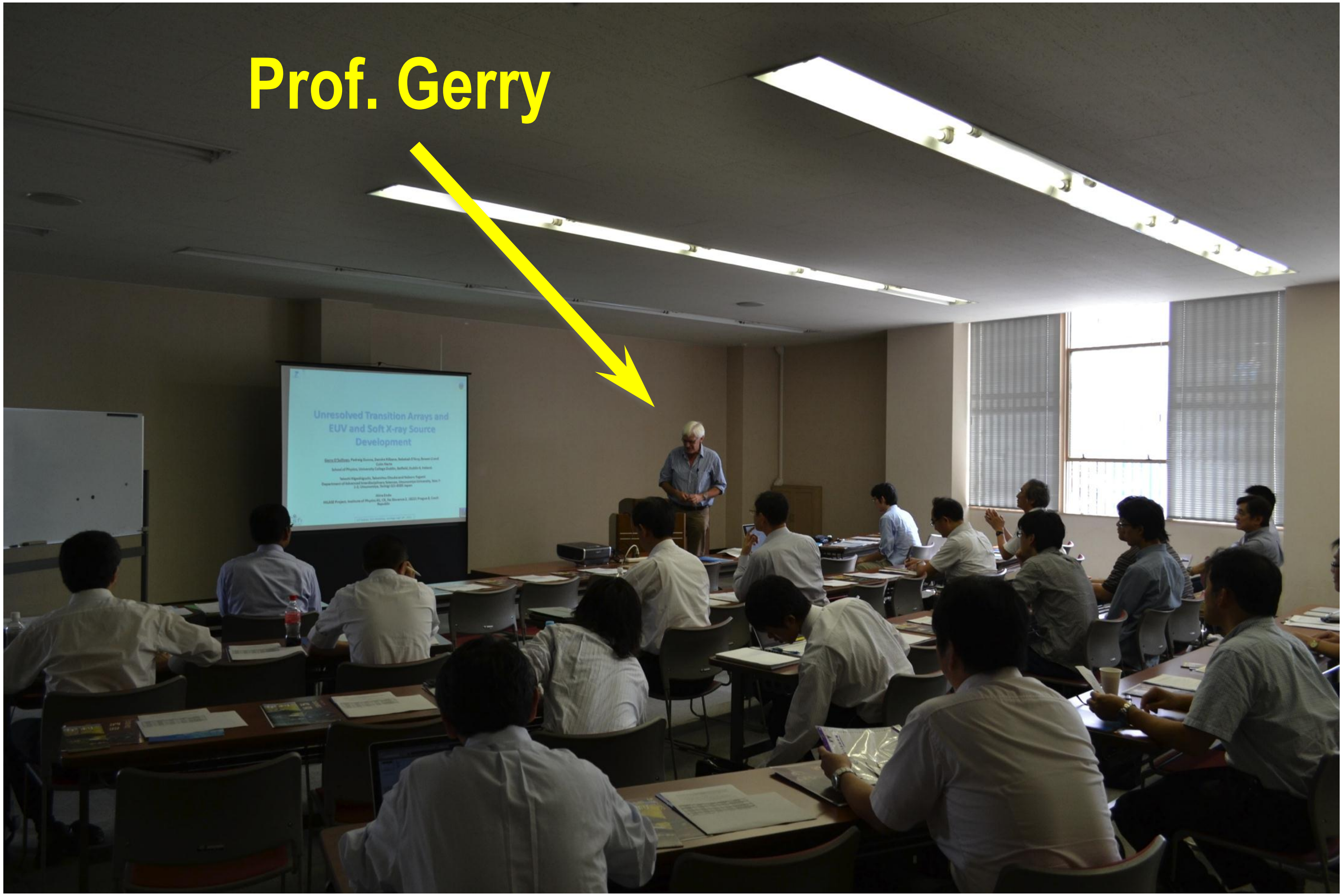
USHIO

GIGAPHOTON

宇都宮大学
UTSUNOMIYA UNIVERSITY

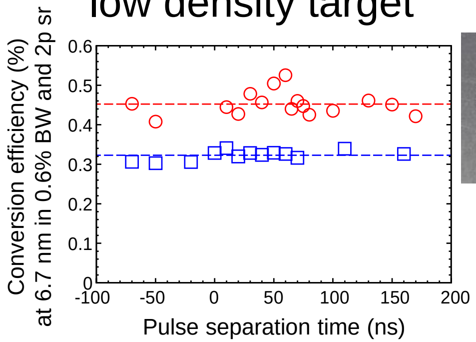
Ad-hoc EUV & BEUV workshop

Ad-hoc EUV & BEUV workshop



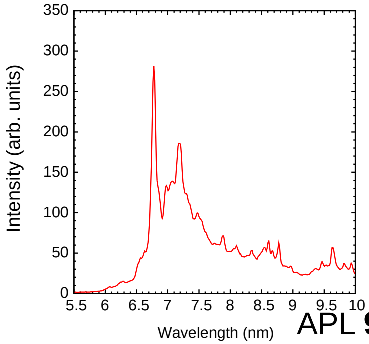
Fundamental property of BEUV sources

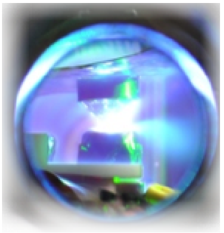
low density target



APL **99**, 191502 (2011).

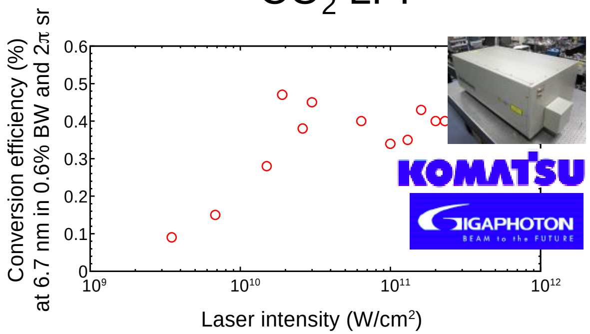
DPP





APL **99**, 231502 (2010).

CO_2 LPP



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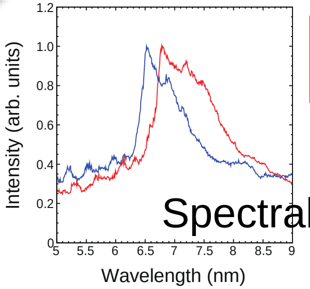
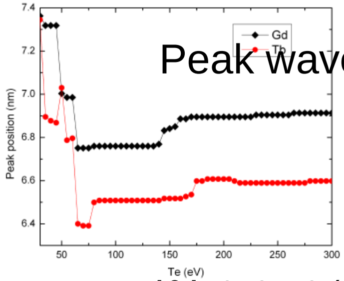


Spectral structure

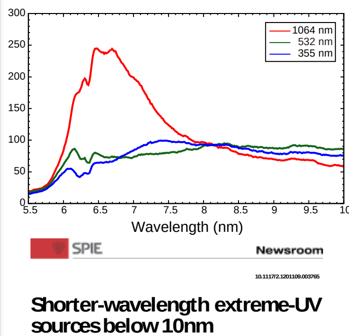
APL **97**, 111503 (2010).

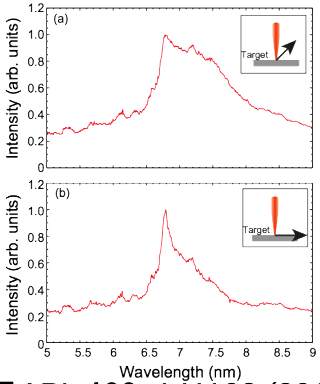


Peak wavelength

APL **101**, 013112 (2012).

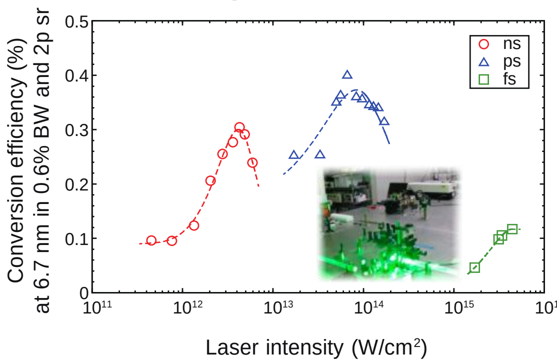
Self-absorption





APL **97**, 231503 (2010). APL **100**, 141108 (2012).

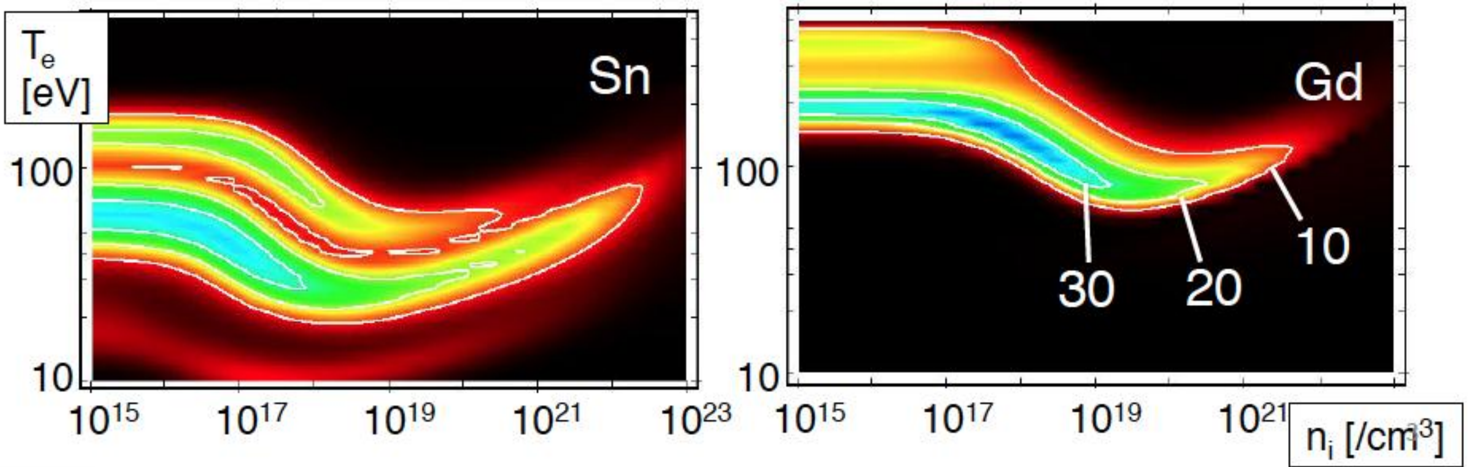
ps LPP



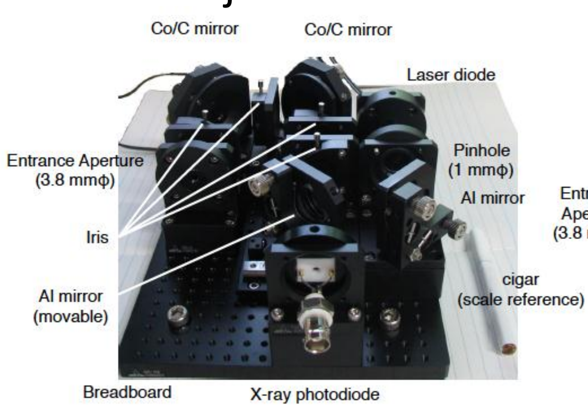
APL **100**, 061118 (2012).

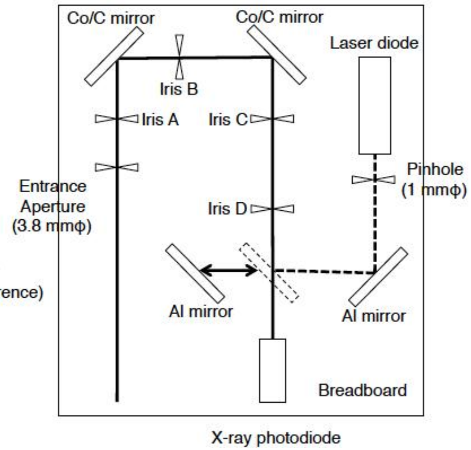
Japan activities for 6.X nm

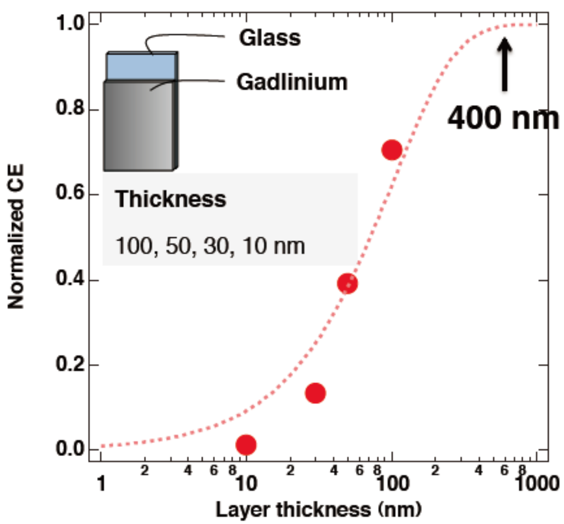
Theoretical
from Dr. Sasaki



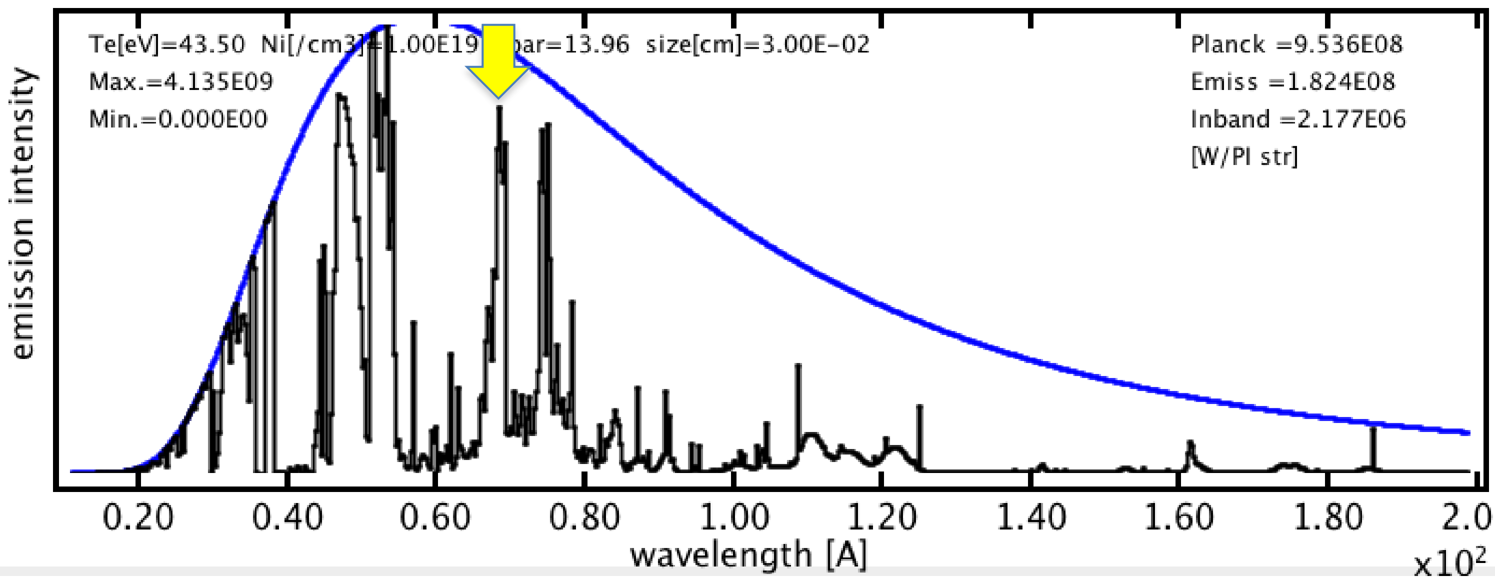
Experimental
from Prof. Fujioka





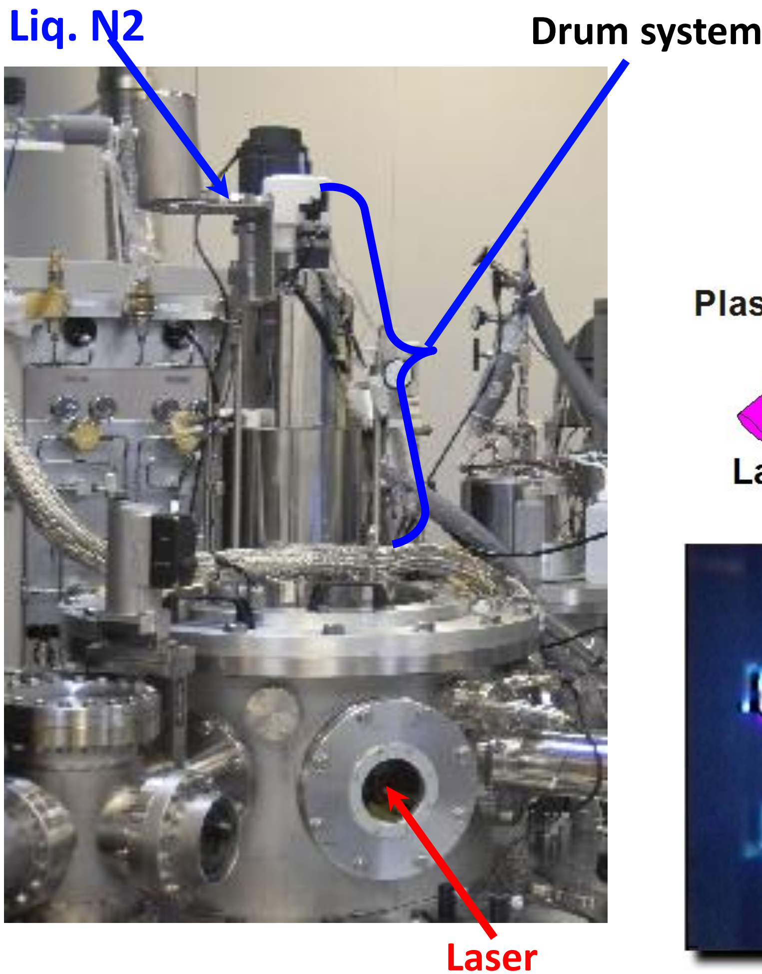


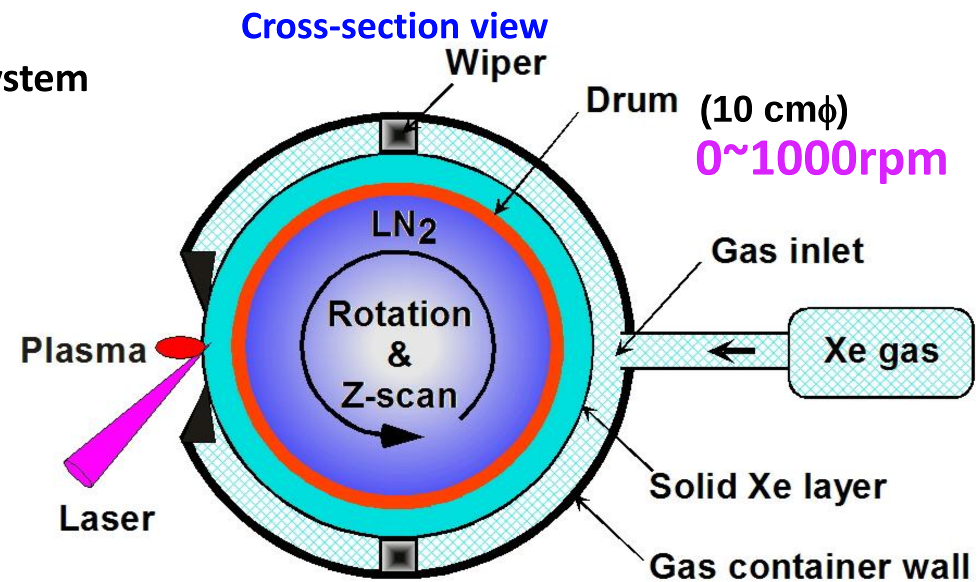
- Optimization in limited parameter space shows Mo plasma with T_e=43eV, n_i=10^{19}/cm^3, and plasma size=0.3mm, 10^6W/πstr of EUV power at 6.5nm (0.5%BW) is obtained with spectral efficiency of 1%.

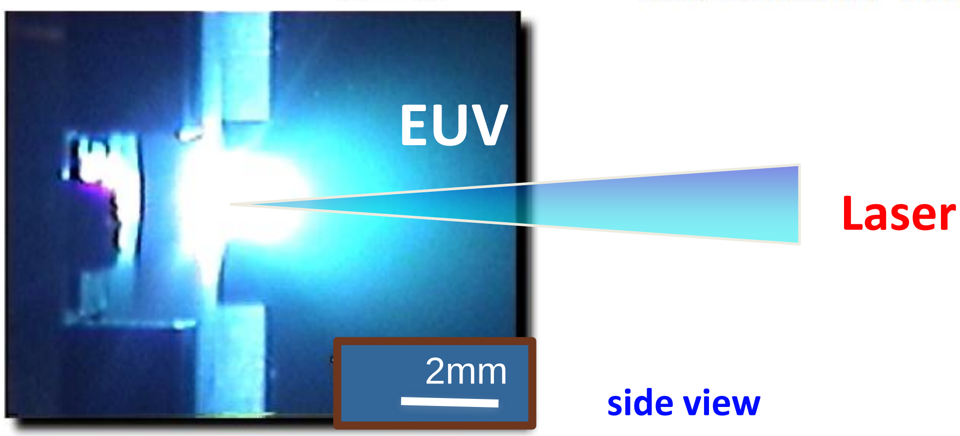


- LTE is assumed.
- Total output power for 10ns, 10kHz pumping is 100W.

Rotating drum cryogenic Xe target

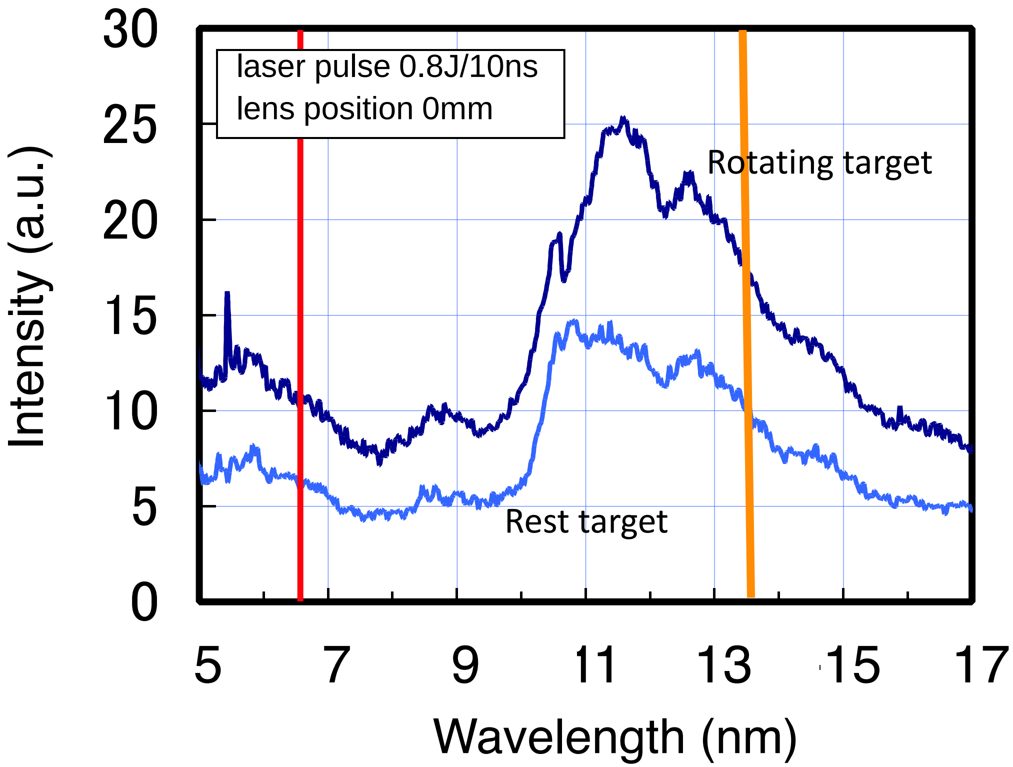






Ref. S.Amano et al, Rev.Sci.Inst.,vol.77,063114(2006).

Measured CE at 6.7nm with 0.6%BW

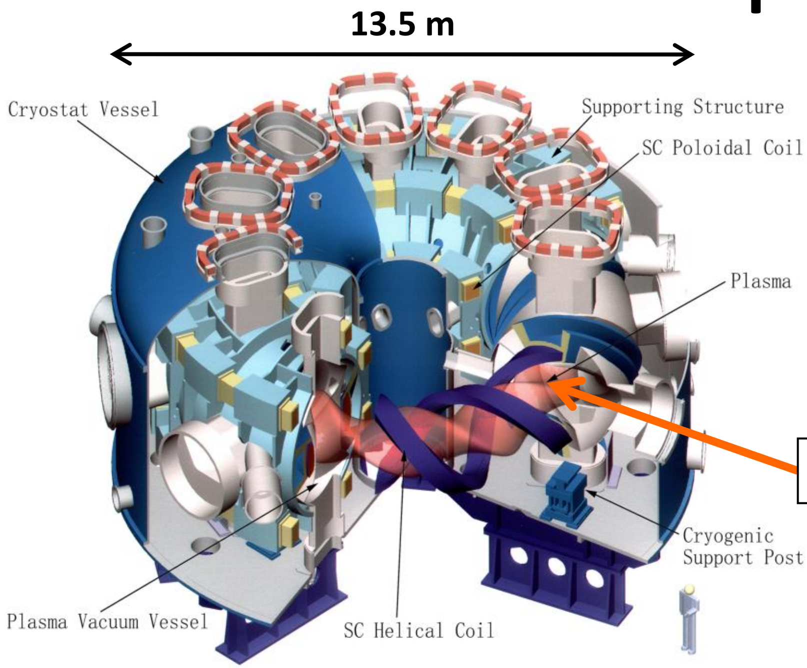


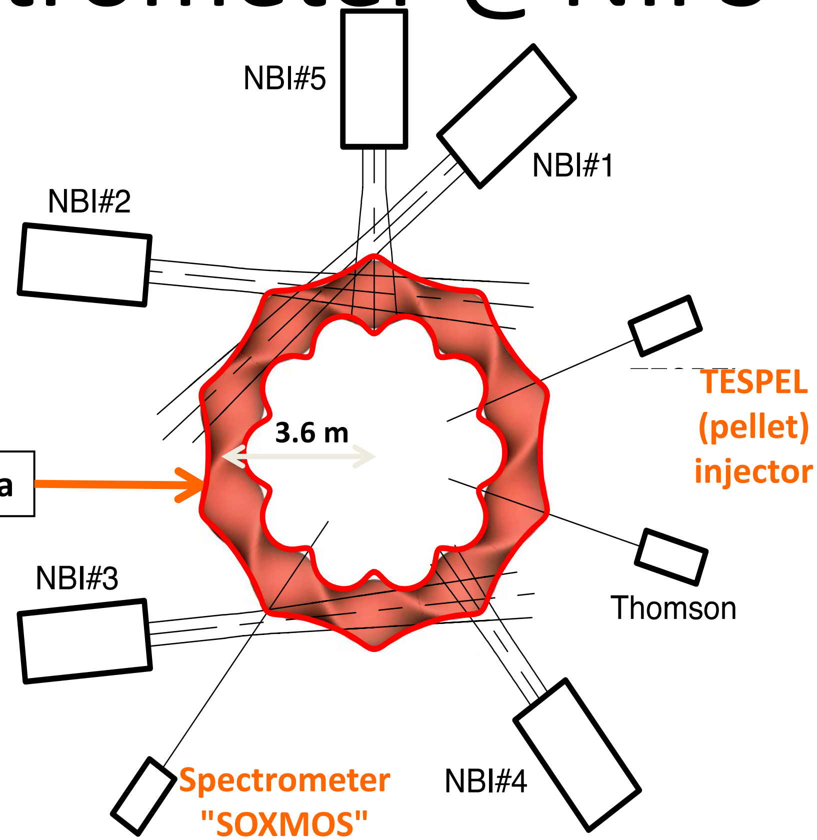
0.15% @I_L =4x10^{12}W/cm^2 (E_L =0.8J)

0.08%@I_L =1.5x10^{10}W/cm^2 (E_L =0.3J)

Ref. S.Amano et al.,"Laser-plasma extreme ultraviolet source at 6.7nm using a rotating cryogenic Xe target", published online in *Appl. Phys. B* .

LHD & VUV spectrometer @NIFS

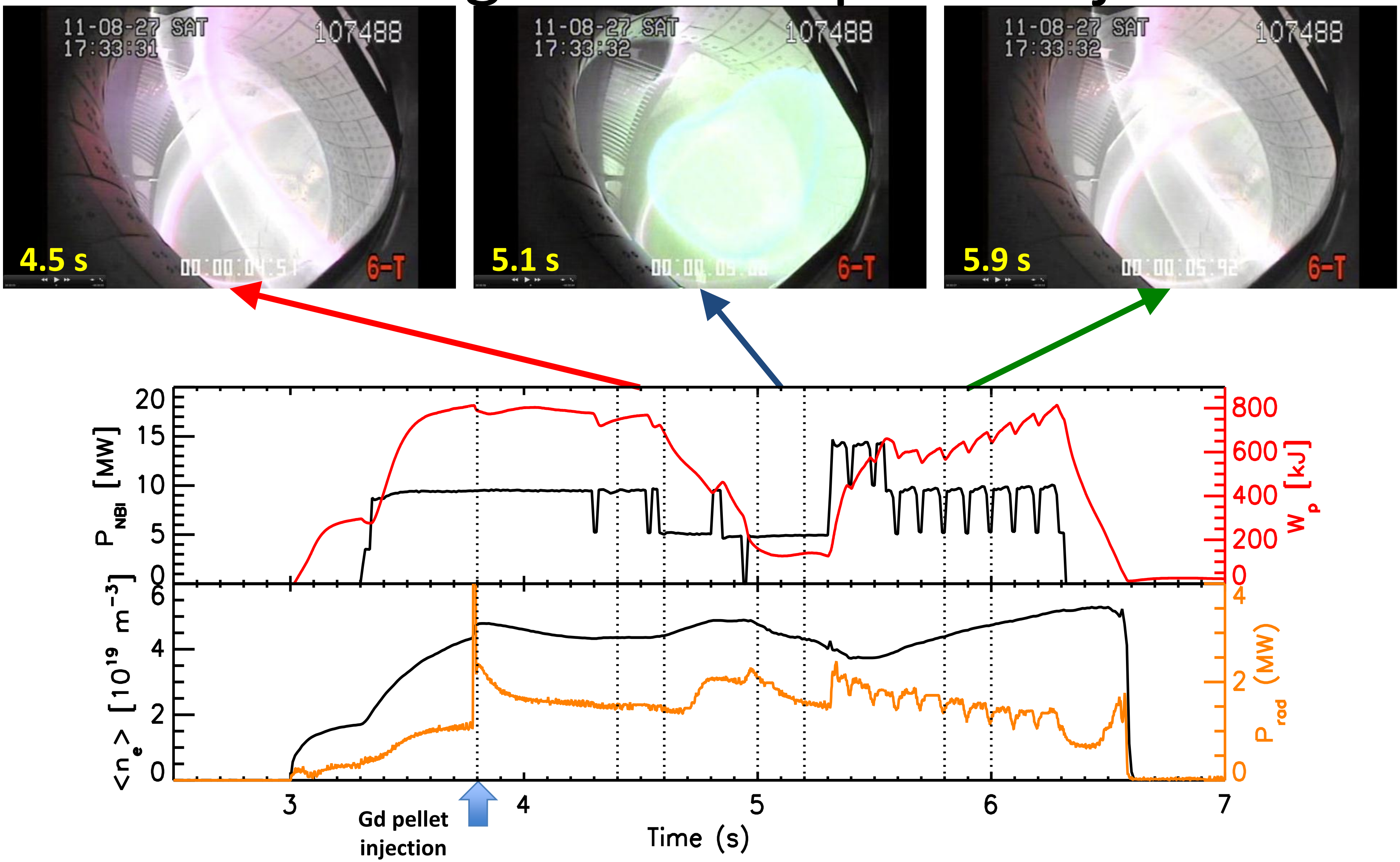




Large Helical Device (LHD)
@NIFS

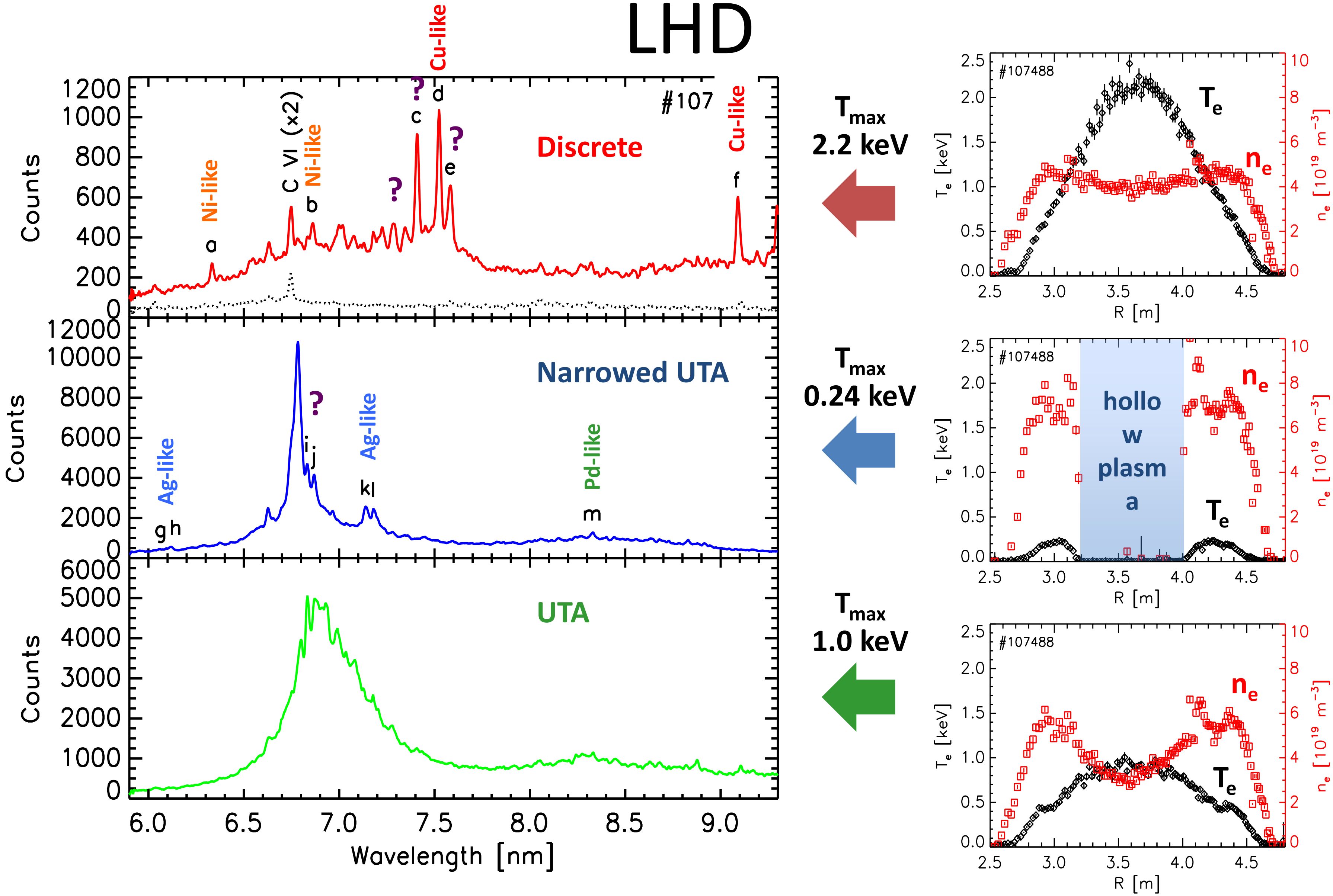
Type	Schwob-Fraenkel 2 m grazing incidence spectrometer
Grooves	133.6 or 600 grooves/mm
Wavelength	1 – 35 nm
Detector	2 MCPs + Phosphor + Photodiode Array
Resolution	~ 0.01 nm

LHD discharge with Gd pellet injection



C. Suzuki *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **45**, 135002 (2012)

Different EUV spectra from Gd ions in LHD

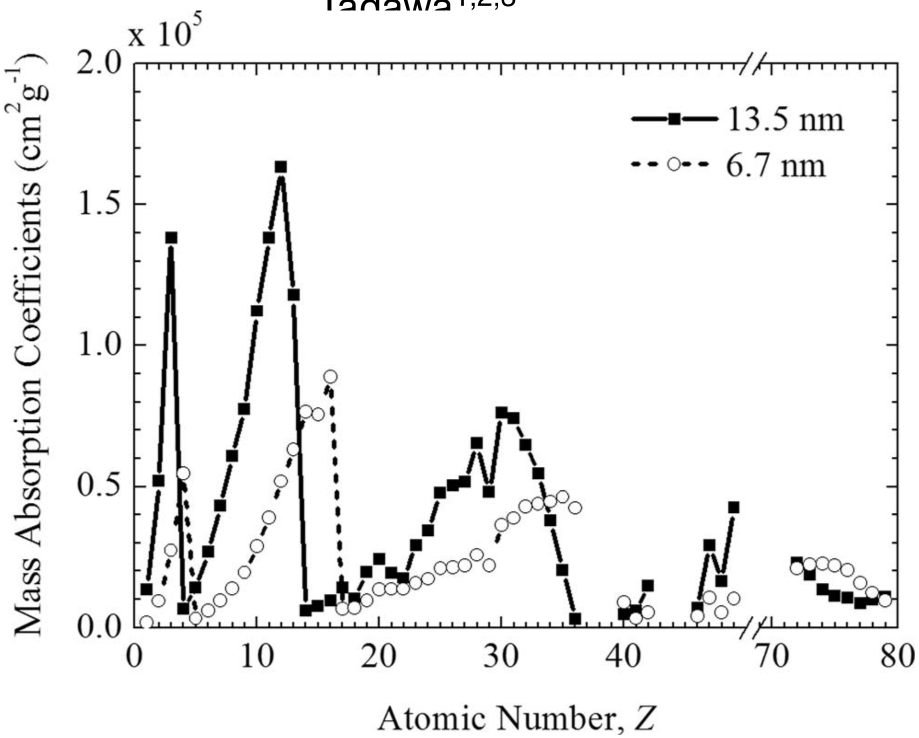


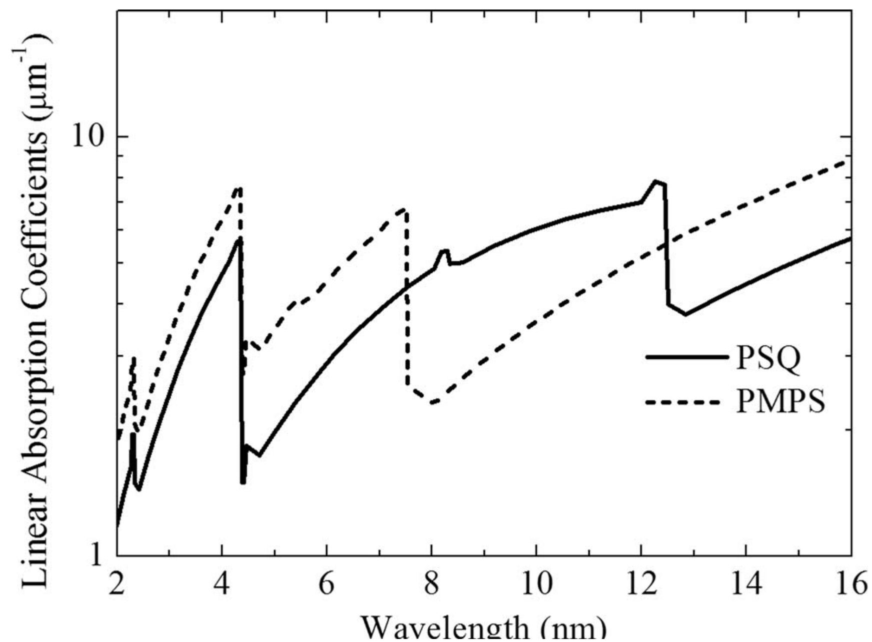
Resist for 6.x nm

AIP ADVANCES **1**, 042153 (2011)

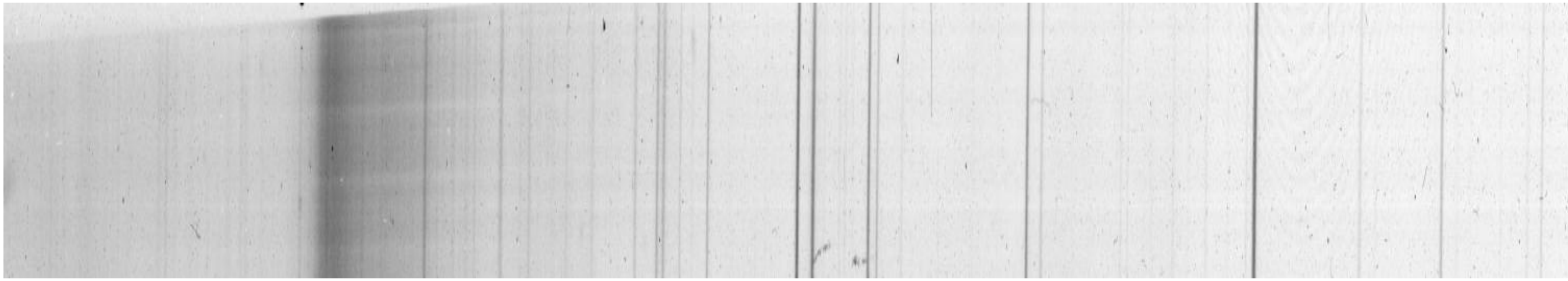
Evaluation of resist sensitivity in extreme ultraviolet/soft x-ray region for next-generation lithography

Tomoko Gowa Oyama,[1,a] Akihiro Oshima,[2] Masakazu Washio,[1] and Seiichi Tagawa[1,2,3]





Typical EUV Spectrum



onsists of:

- Lines (bound-bound transitions), because of high density, lines from high n states are usually not seen
- Recombination Radiation (bound-free transitions) which scales as $\langle\zeta\rangle^4$ where $\langle\zeta\rangle$ is the average ionic charge
- Bremsstrahlung (free-free)

For an optically thin plasma: P_{lines}:P_{recomb}:P_{brem} = 100:10:1

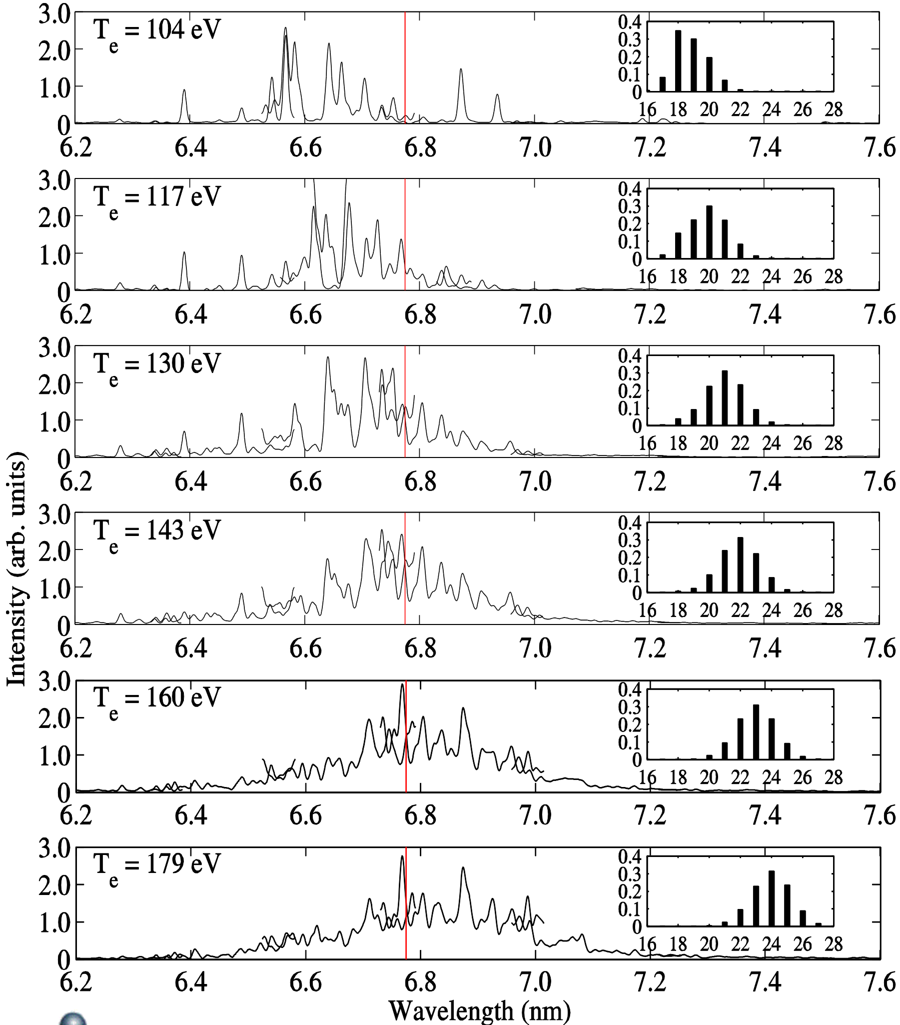
In some cases lines cluster together to form a UTA (unresolved transition array)

FAC code calculations for Gd

JOURNAL OF APPLIED PHYSICS 108, 104905 (2010)

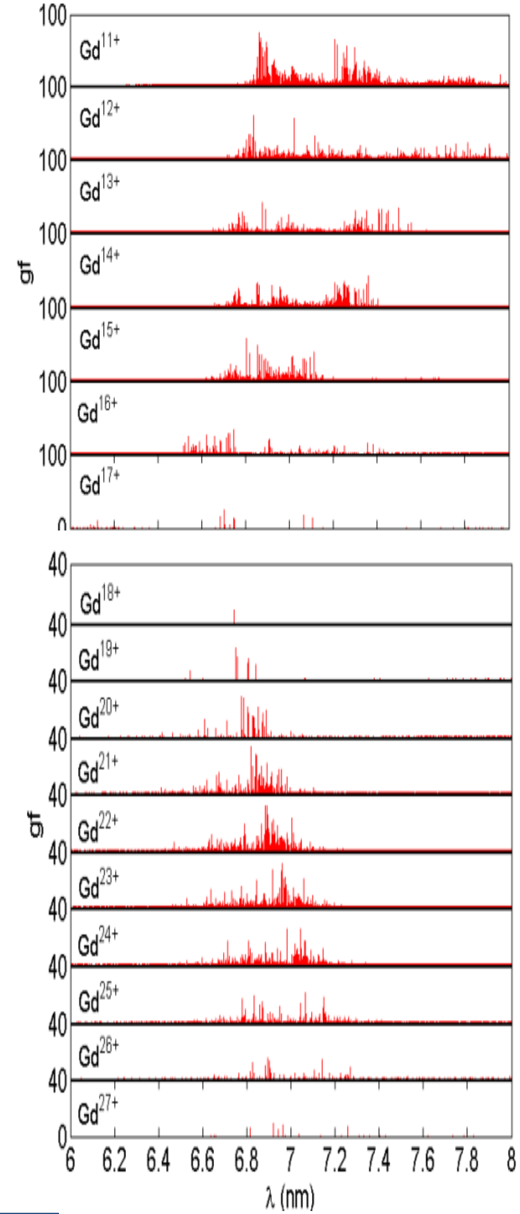
Extreme ultraviolet emission spectra of Gd and Tb ions

D. Kilbane[a] and G. O'Sullivan
School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

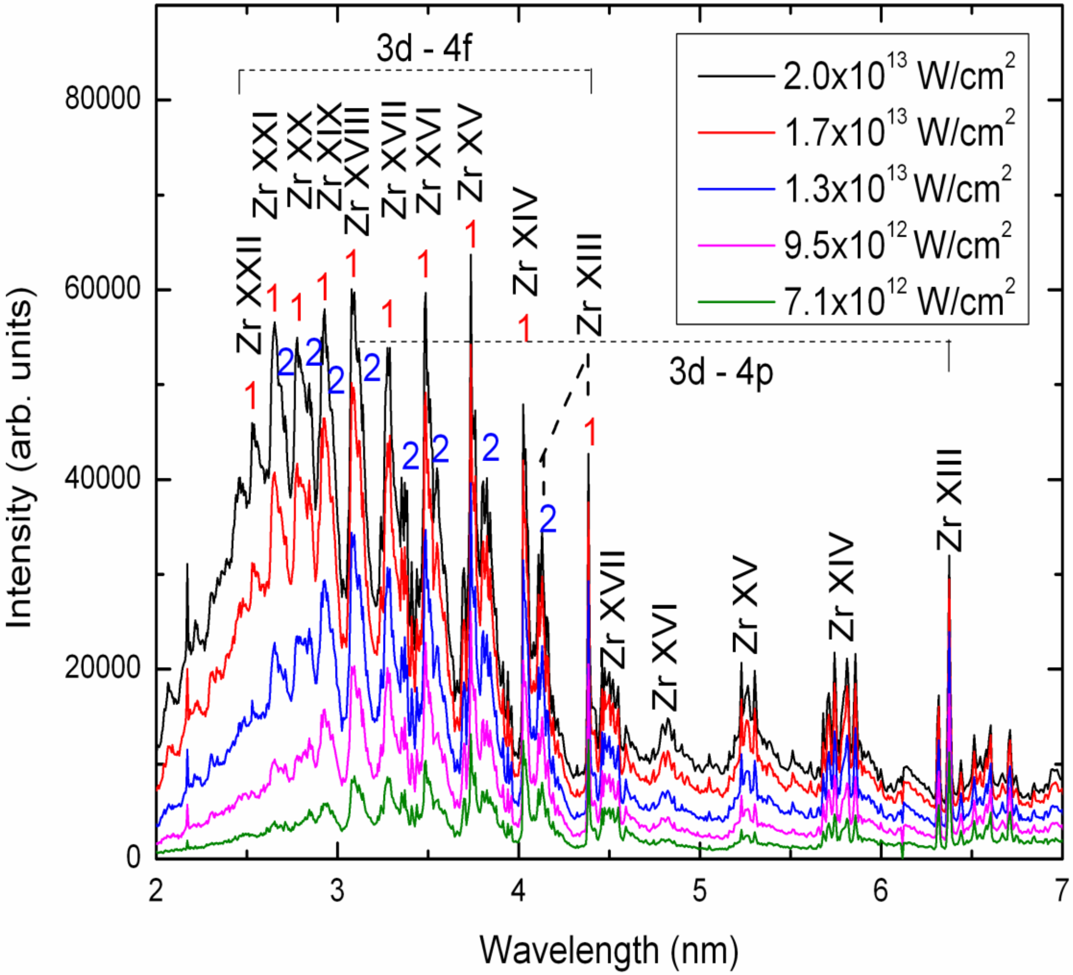


Calculations more complex than for Sn because of open 4f subshell in ions lower than 18+

In low stages, 4f, 5p and 4f, 5s level crossings give rise to very complex interacting configurations



Δn = 1 3d-4f and 3d-4p UTA emission from Zr



Spectral behavior of Zr plasmas as a function of laser laser intensity

Resonant 3*d*–4*f* (1) and 3*d*–4*p* transitions as well as satellite lines from $3d^{n-1}4s4f$–$3d^{n-2}4s4f$ (2)

一流体二温度の圧縮性流体の基礎方程式

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\vec{v} = 0$$

continuity equation

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla(p+q)$$

momentum equation

$$\rho c_{vi}\frac{DT_i}{Dt} = \underbrace{-\left\{T_i\left(\frac{\partial p_i}{\partial T_i}\right)_\rho + q\right\}\nabla\cdot\vec{v}}_{\text{pdV work}} + \alpha(T_e - T_i) + \underbrace{\nabla\cdot(\kappa_i\nabla T_i)}_{\text{イオン熱伝導}}$$

ion energy equation

$$\rho c_{ve}\frac{DT_e}{Dt} = \underbrace{-T_e\left(\frac{\partial p_e}{\partial T_e}\right)_\rho\nabla\cdot\vec{v}}_{\text{pdV work}} - \underbrace{\alpha(T_e - T_i)}_{\text{イオン一電子温度緩和}} + \underbrace{\nabla\cdot(\kappa_e\nabla T_e)}_{\text{電子熱伝導}} + S_L + S_{Rad}$$

electron energy equation

流体

$$S_L = (k_L\cdot\nabla)\cdot I_L$$

Laser heating term

レーザー

$$\rho\frac{D}{Dt}\left(\frac{E_\nu}{\rho}\right) + \nabla\cdot D_\nu\nabla E_\nu = 4\pi\eta_\nu - c\chi_\nu E_\nu$$

multi-group diffusion approximation

$$S_{Rad} = -\int(4\pi\eta_\nu - c\chi_\nu E_\nu)d\nu$$

Radiation heating term

輻射

状態方程式で与えられる

原子過程計算で与えられる

Energetics

1.06μm case

Laser $\xrightarrow{1.0}$ Plasma $\xrightarrow{0.6}$ x-ray $\xrightarrow{0.05}$ EUV 3%

Plasma $\xrightarrow{0.4}$ ionization, kinetic, thermal

CO2 short pulse (<20ns)

Laser $\xrightarrow{0.5}$ Plasma $\xrightarrow{0.25}$ x-ray $\xrightarrow{0.25}$ EUV 3.1%

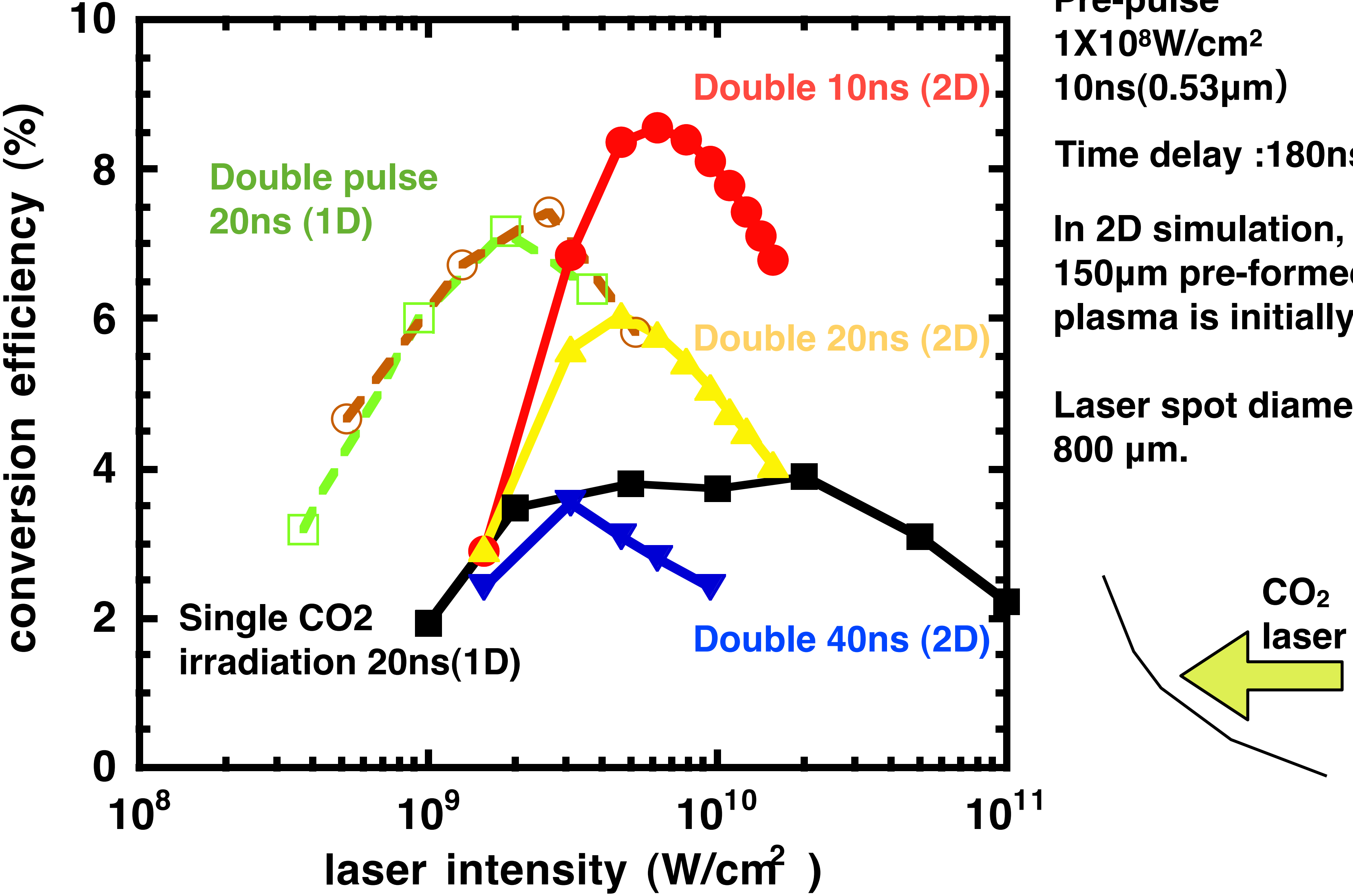
Plasma $\xrightarrow{0.75}$ ionization, kinetic, thermal

CO2 long pulse (>40ns)

Laser $\xrightarrow{0.5}$ Plasma $\xrightarrow{0.5}$ x-ray $\xrightarrow{0.1}$ EUV 2.5%

Plasma $\xrightarrow{0.5}$ ionization, kinetic, thermal

Double pulse scheme with CO2 main pulse can give 6-8% EUV CE which is twice of that given by single CO2 irradiation on tin target.



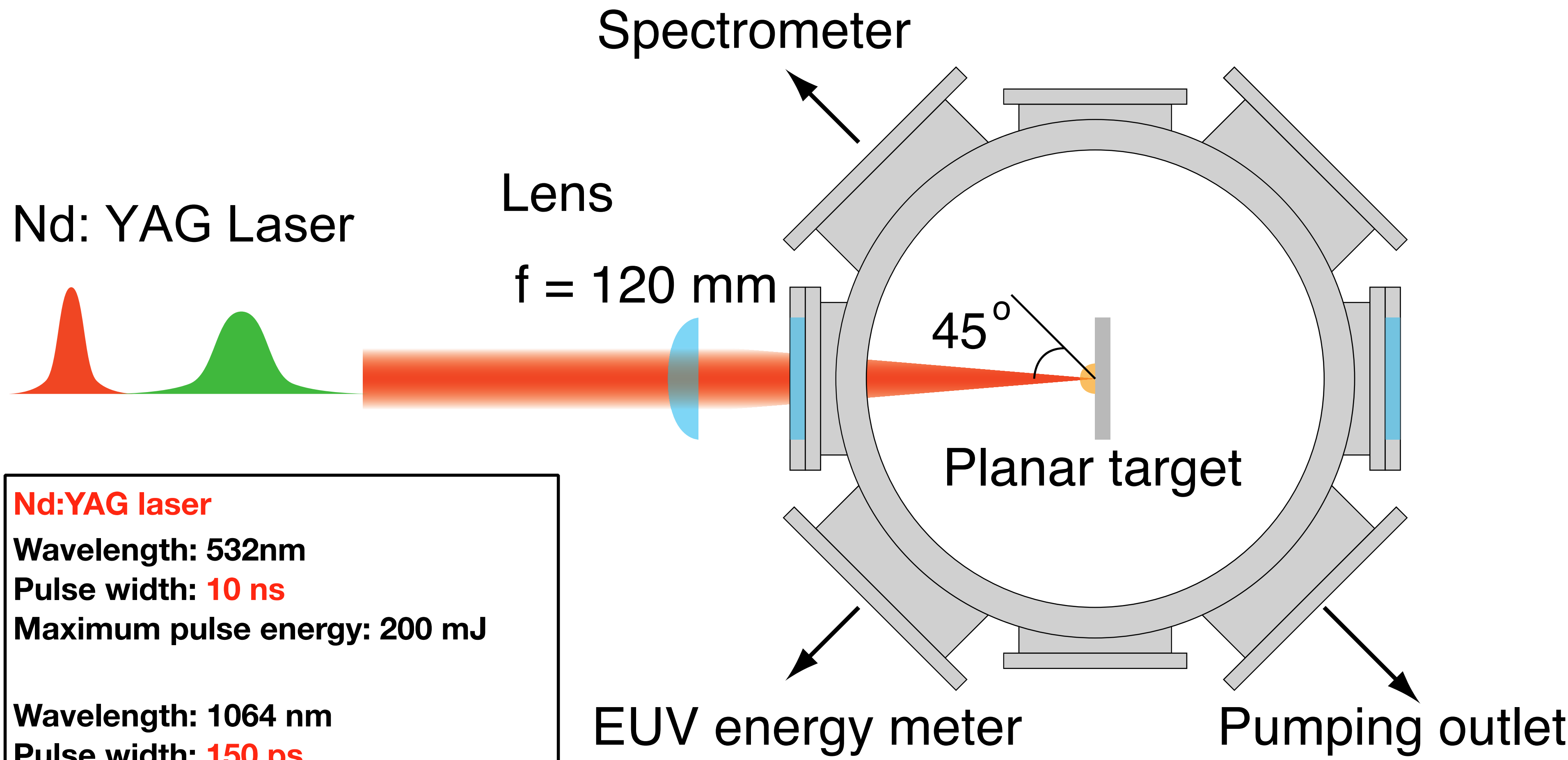
Pre-pulse
$1X10^8 W/cm^2$
10ns(0.53μm)

Time delay :180ns

In 2D simulation, 150μm pre-formed plasma is initially set.

Laser spot diameter: 800 μm.

Experimental setup

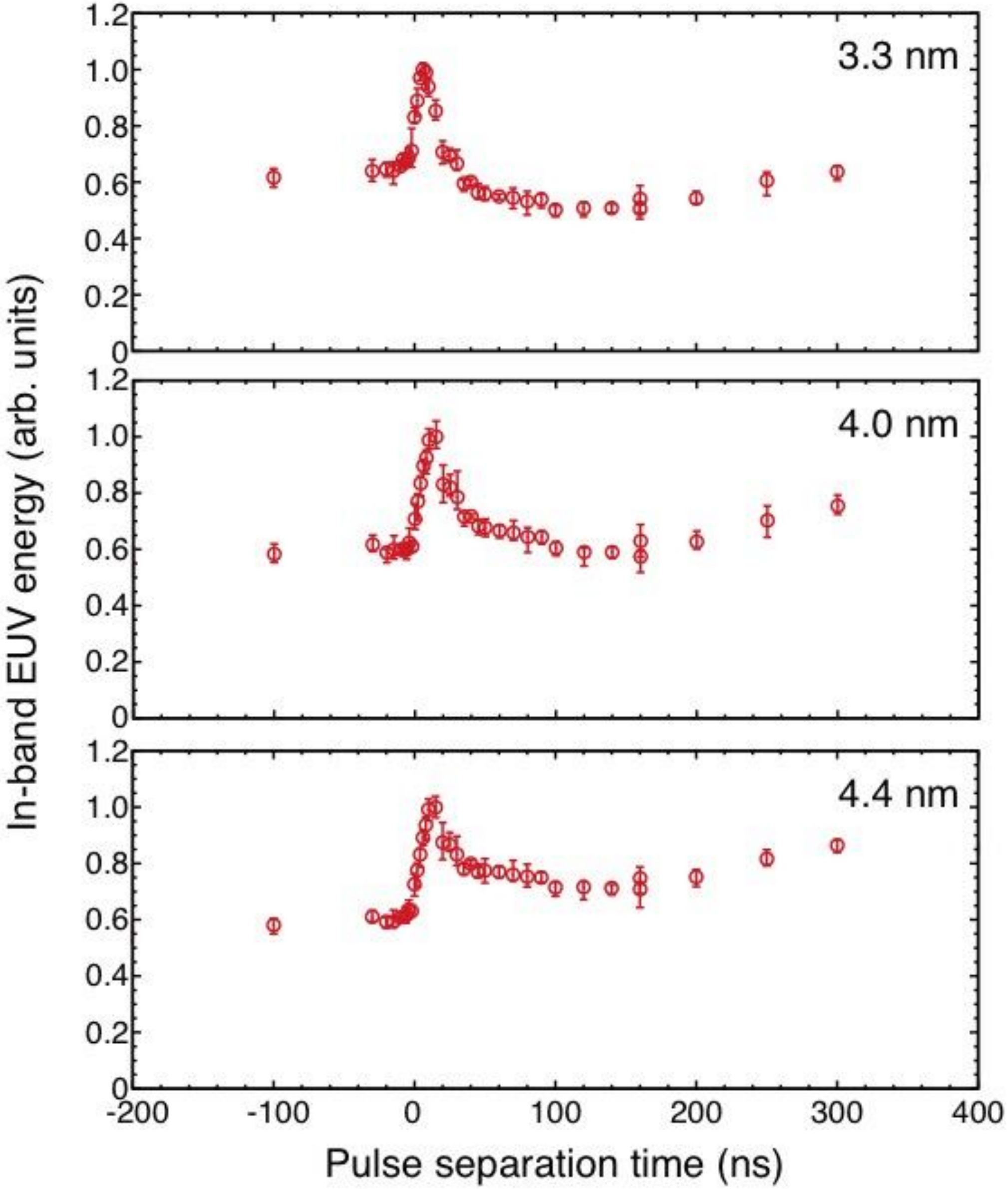


Nd:YAG laser

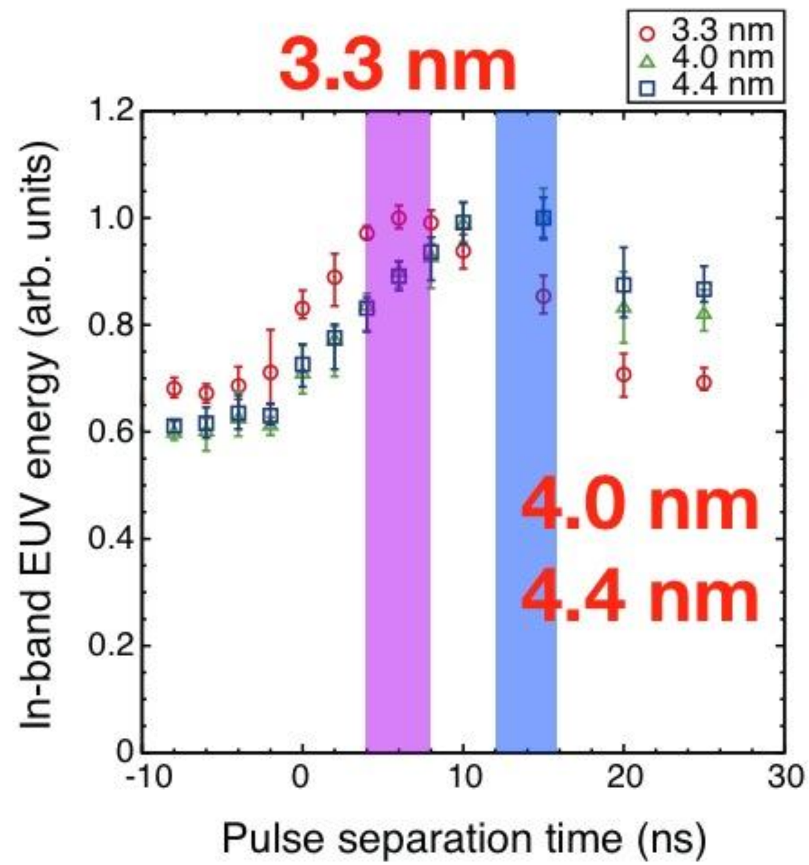
Wavelength: 532nm
Pulse width: 10 ns
Maximum pulse energy: 200 mJ

Wavelength: 1064 nm
Pulse width: 150 ps
Maximum pulse energy: 220 mJ

In-band EUV energy depend on pulse separation time



BW: λ ± 0.01 nm



OPA & CO_2 multi-pass amplification

OPA out

- 100 - 200 μW (10 - 20 μJ@10Hz)
- 10.6 μm

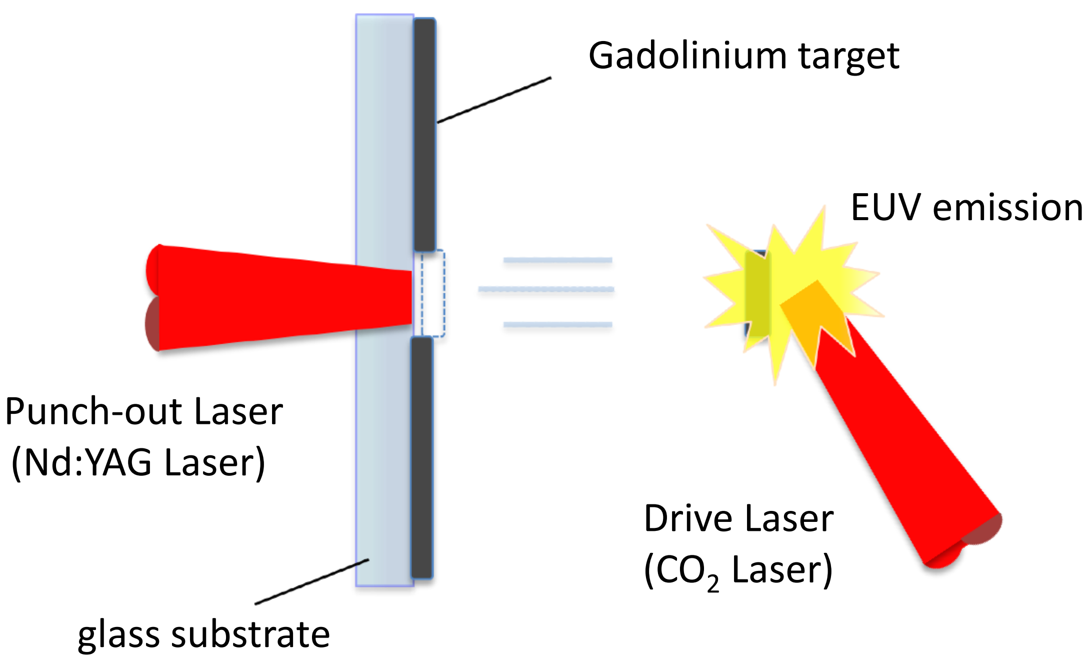
CO_2 multi-pass amplification

- Seed pulse energy: 160 μJ
- Output pulse energy (10 pass): ＞150 mJ

Punch-out is a new method to supply plasma sources for 6.Xnm BEUV light generation.

It is difficult to generate Gadolinium droplets because melting temperature of Gd is "1585K" that is much higher than "595K" of tin's melting temperature.

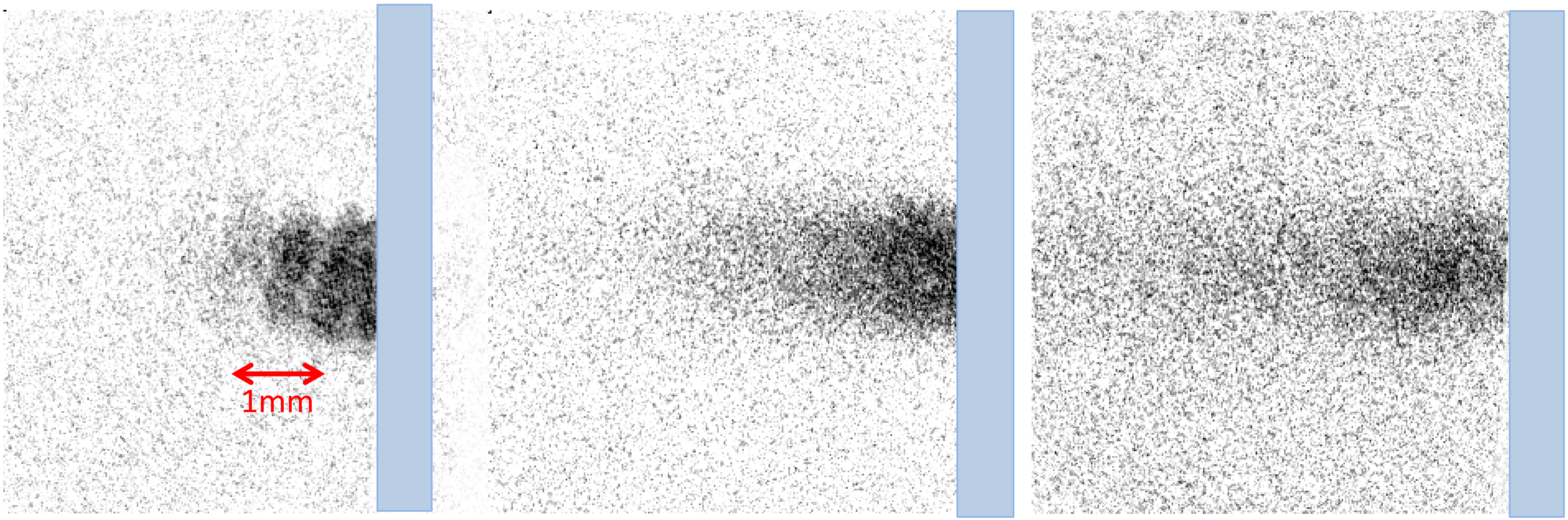
Punch-out target supply method



Condition for practical

Frequency:
10kHz
Punch-out laser energy:
under 100mJ
Flying speed:
over 100m/s
Flying distance:
over 10mm

Gd mist can be supplied by using the punch-out scheme.



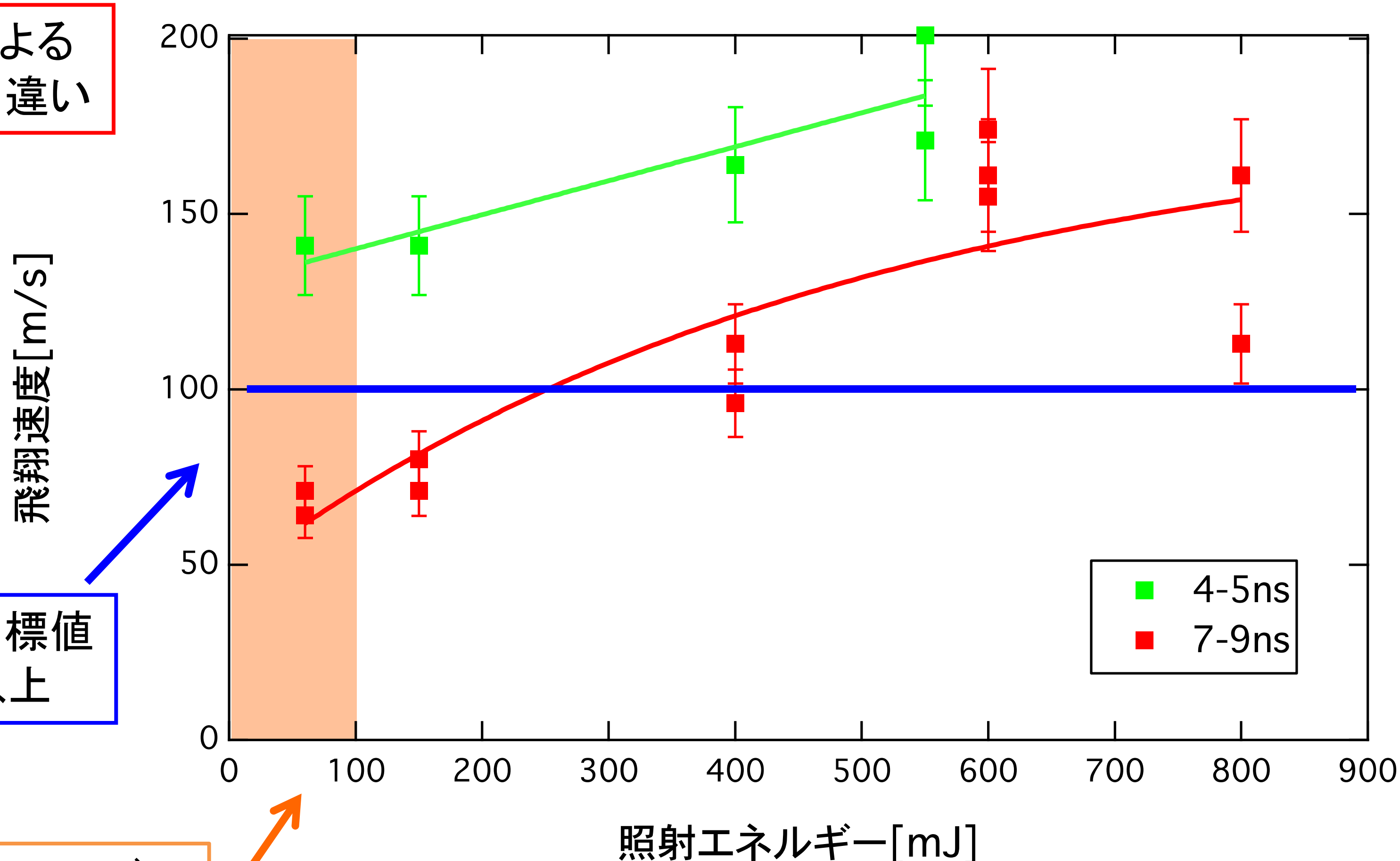
Delay 1μs → Delay 3μs → Delay 5μs

Energy	:70mJ
Pulse width	:300ps
Laser Intensity	:7×10^{9} W/cm^2
Target thickness	:3μm

パルス幅が短いほうが飛翔速度が速くなると考えられる

ILE OSAKA

パルス幅による
飛翔速度の違い

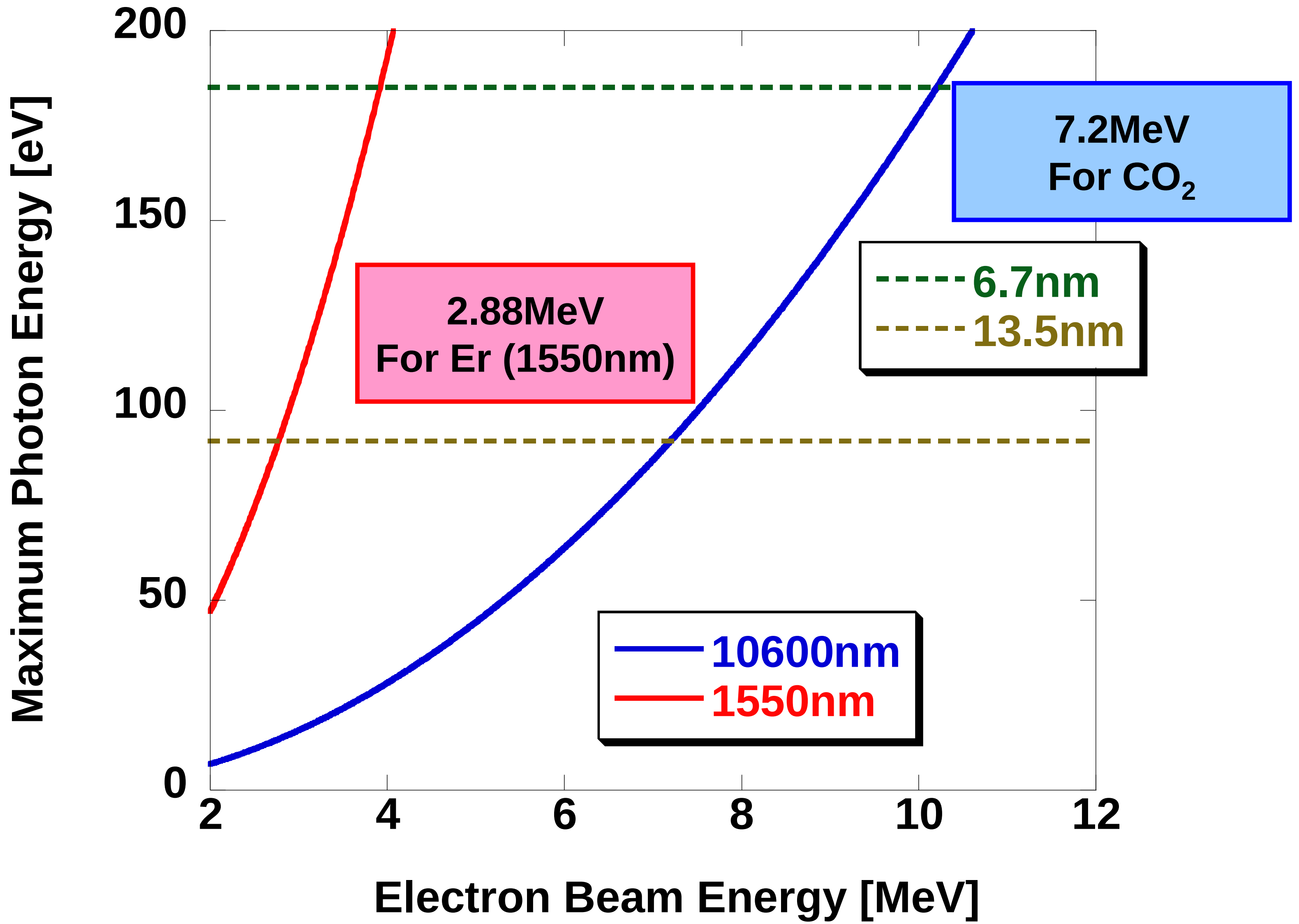


飛翔速度目標値
約100m/s以上

パンチアウトレーザー
エネルギー目標値
約100mJ/shot以下

パルス幅4~5nsの時のほうが飛翔速度が速いのは
レーザー強度が高くなったためだと考えられる

Laser Compton Scattering

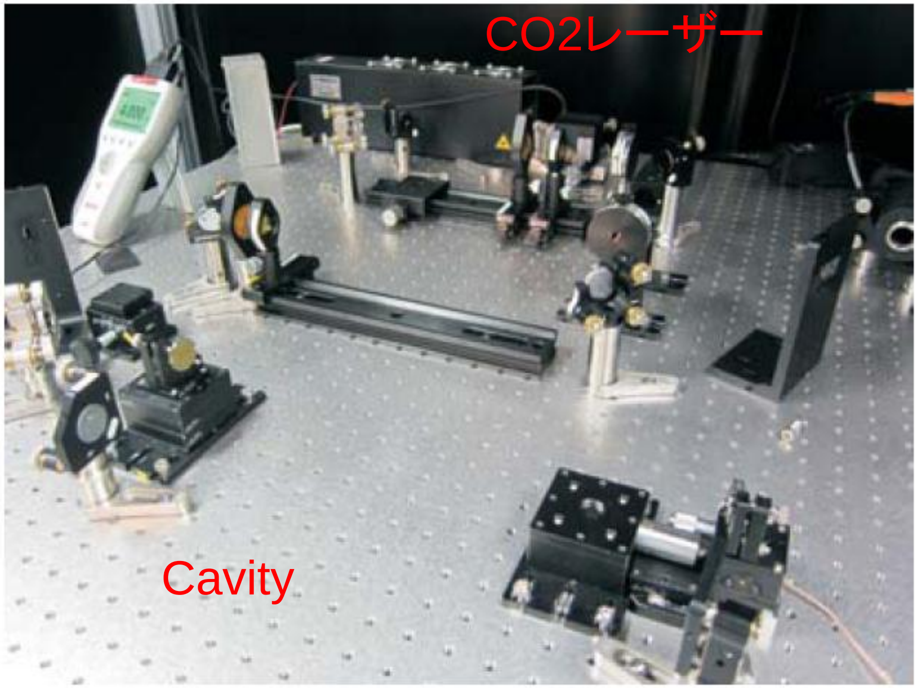


CO2 Laser Super-Cavity R&D

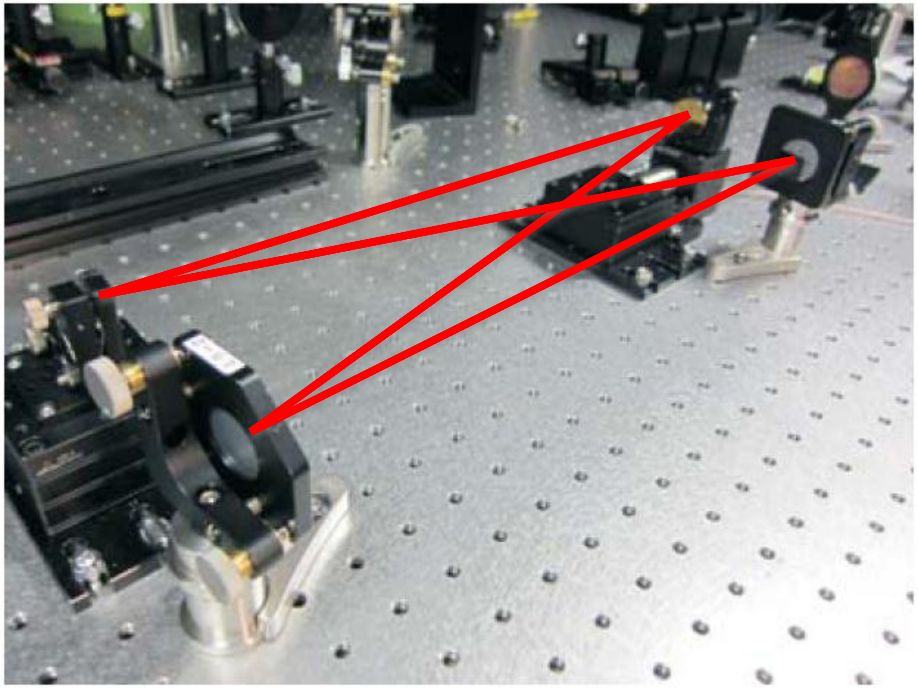
早稲田大学におけるCO2レーザー蓄積共振器開発の様子

CWのレーザー光の蓄積実証試験を行っている

Exp. Setup



Cavity Setup　4M平面

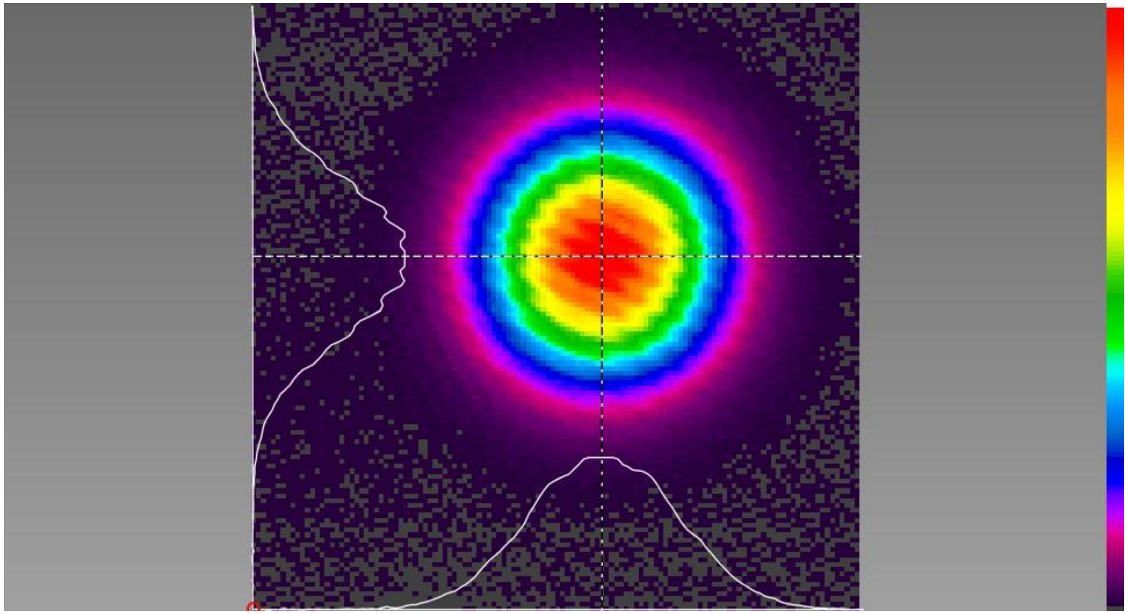


CO2 Laser Super-Cavity R&D

10um用Cavityからの透過光プロファイル

＞ほぼTEM00の綺麗なプロファイル。

波打っているのはプロファイラの特性

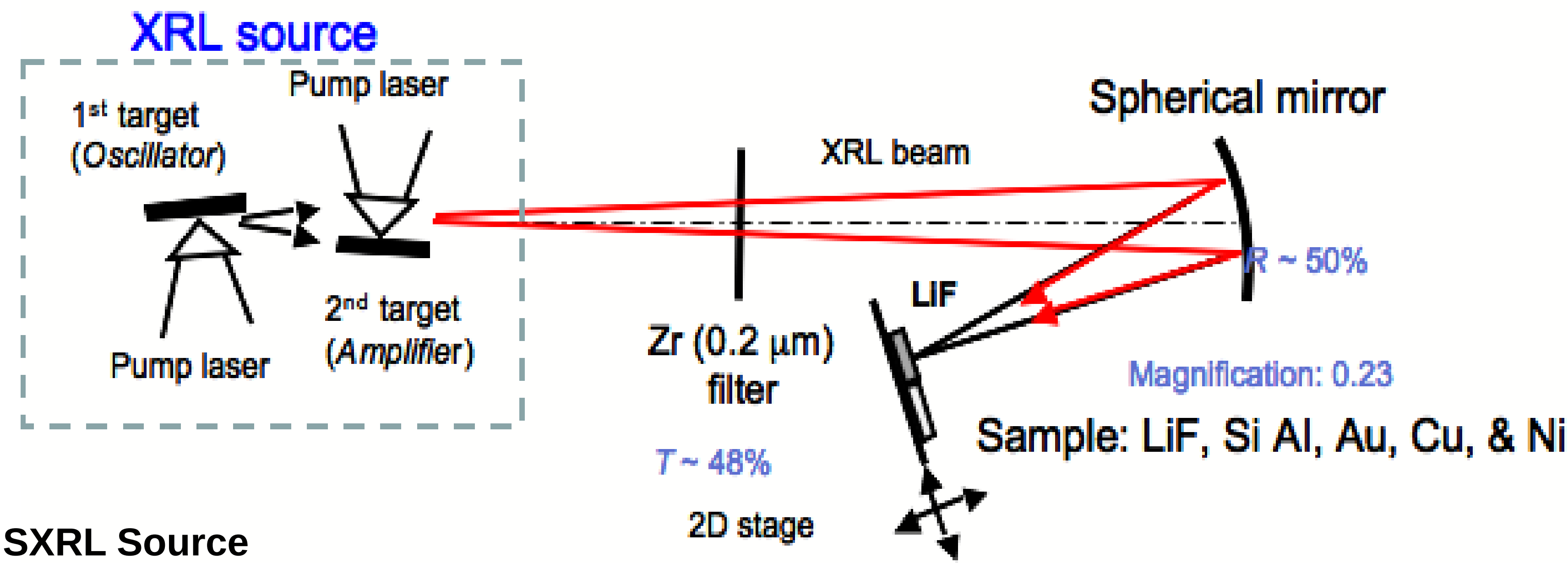


実際に10umの光の蓄積が可能であること、

市販のコンポーネントを組み合わせても50倍程度の増大率は得られること

を確認した。

Experimental set-up



SXRL Source

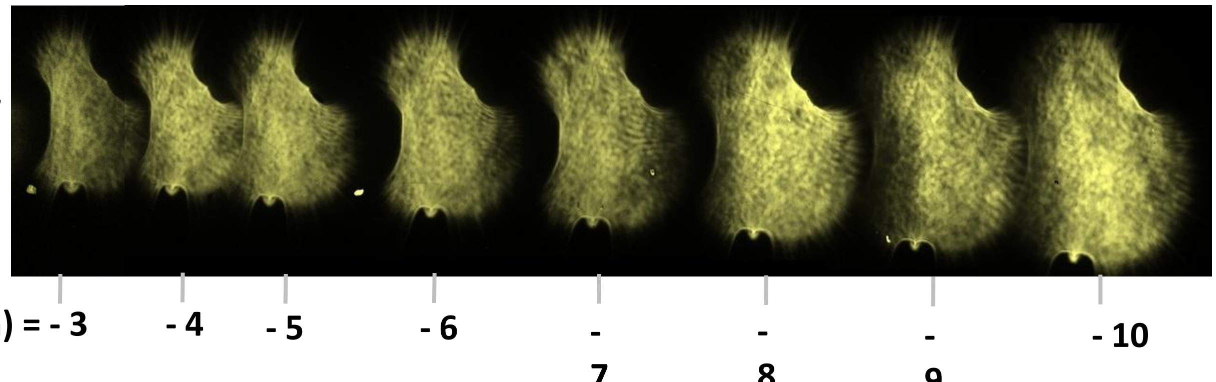
Wavelength: λ= 13.9 nm (E = 89.2 eV)
Pulse Duration: Δt = 7 ps
Output Energy: 200–300 nJ/shot

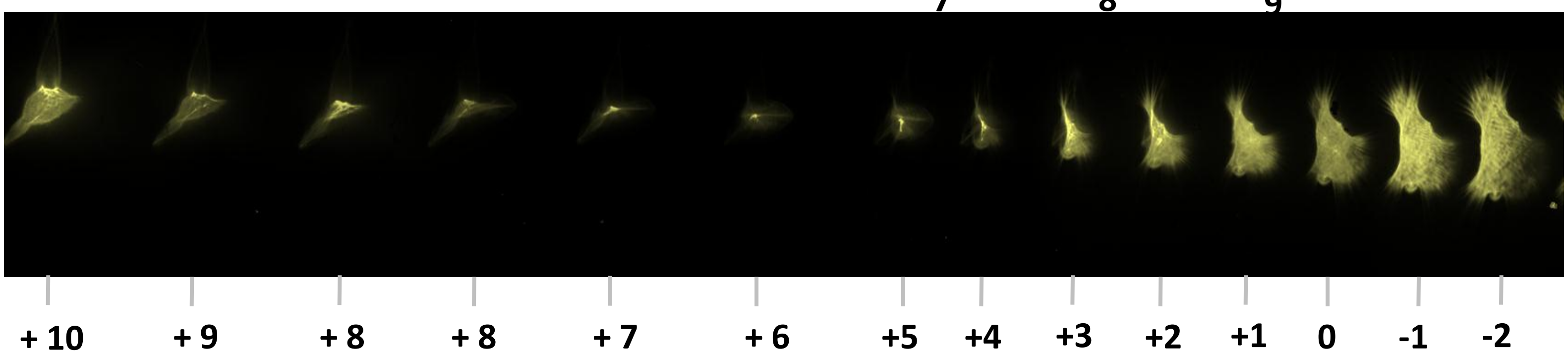
Total Energy of SXRL beam

At Sample Surface: 48–72 nJ/shot
Average Fluence: 1 - 100 mJ/cm^2

EUV laser spot patterns are recorded by LiF detector.

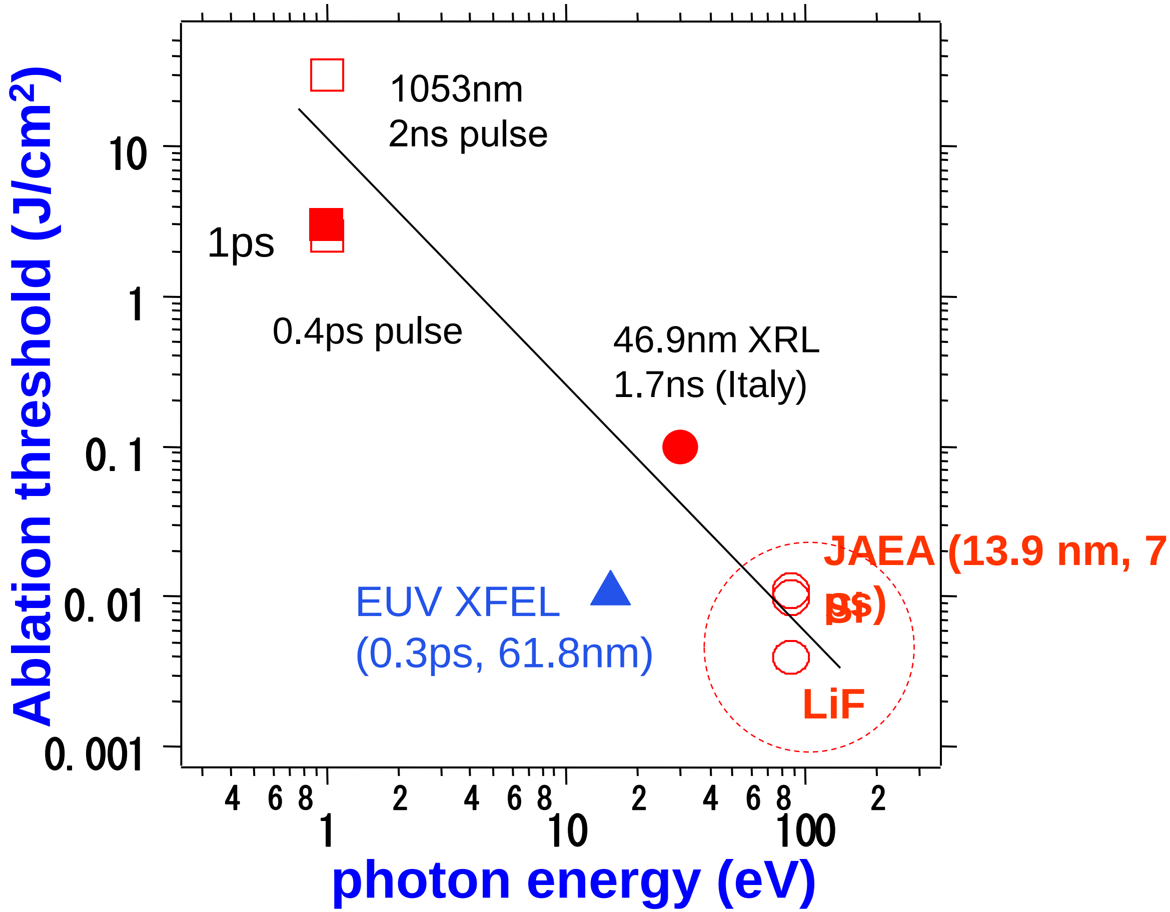
Images of X-ray laser spots, obtained on the LiF detector:





A.Ya. Faenov, et al., Optic Letters 34, 941 (2009)

XRL (EUV) laser ablation for LiF and Si



The result shows that the ablation threshold (fluence) for the SXRL is smaller by 2-3 orders of magnitude compared with that of IR laser.

JSAP, JPS, LSJ Ad-hoc workshop

Sep. 11th: JSAP @ Matsuyama

Sep. 18th: JPS@Yokohama

Sep. 26th: LSJ@Ashikaga

Ad-hoc EUV & BEUV workshop

Thanks a million!!!